Development of Hybrid Anti-Rolling Device for Ships and Test at Sea

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Development of Hybrid Anti-Rolling Device for Ships and Test at Sea

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1. Introduction

The attenuation of hull rolling while a ship is running at slow speed and while drifting, is an essential requirement for vessels engaging in meteorological observations and in oceanographic surveys. Devices for attenuating hull rolling have conventionally incorporated either anti-rolling tanks or fin stabilizers. The former system–which functions on the lift generated by controlled-angle fins–cannot be operated without the ship running. Conversely, while the device is in action, it generates additional drag against the ship's progress. The latter anti-rolling tank system, on the other hand, presents the disadvantages of (a) obstructing the view aft with its tanks, which are usually installed above the upper deck, and (b) being effective only against a designated frequency of hull rolling and being adjustable to cover variations in the hull rolling period, which would change with the loading and other ship conditions. With a view to eliminate the foregoing shortcomings of conventional anti-rolling devices, the present authors have applied to shipboard use the system functioning by moving mass, whose movement is controlled by an actuator. Tests at sea on a model unit constructed on this principle have proved that such a system ensure satisfactory performance.[1]

Oscillation attenuating devices functioning by moving mass–currently applied to land structures–comprise three types: (a) passive, (b) active, and (c) hybrid. The latter two types, both have their moving mass driven by an actuator; the hybrid type is a combination of the active and passive types, with the moving mass driven in parallel by both spring/damper and actuator systems. The hybrid mode of functioning presents the merits of (a) calling only for a smaller actuator capacity to provide roughly equal rolling attenuation performance as compared with a purely active-type device, and (b) being able to continue functioning as a purely passive device in the event of power source failure. These characteristics should also make this type of device adaptable for application on large ships.[2,3]

The present study covers the development of a hybrid-type anti-rolling unit designed for installation on a survey supervising vessel of approximately 190 t displacement, followed by a test conducted at sea on the equipped vessel. The test results revealed the notable performance of reducing to approximately 1/3 the hull rolling of a ship left to drift in broadside waves.

2. Design of control system

Based on the dynamic model shown in *Fig. 1*, the actuator control system has been designed by adopting the following assumptions.

(1) Hull rolling is limited to rotative motion around the ship's centre of gravity; all coupling with movements in the remaining degrees of freedom are neglected.

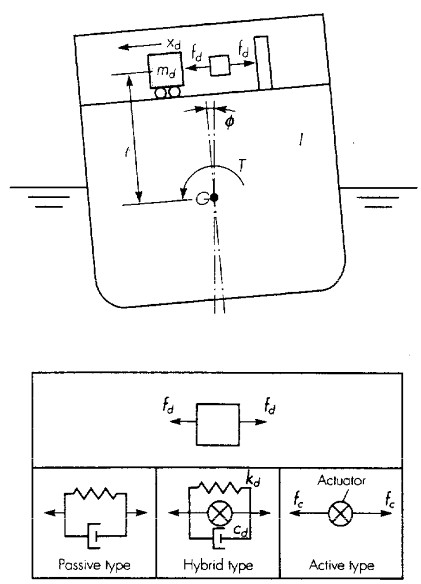


Fig. 1 Dynamic model

(2) Damping of hull rolling is of viscous mode.

With a hybrid type anti-rolling device, the movements of the hull and of the moving mass can be expressed in linearized form as

$$I\ddot{\phi} + R\dot{\phi} + W\,\overline{GM}\,\phi$$
$$= T + m_d g\,(x_d - \ell\phi) - f_d\,\ell \quad \text{.............. (1)}$$

$$m_d\,\ddot{x}_d = m_d g\phi + f_d \quad \text{.............................. (2)}$$

$$f_d = f_c + c_d\,(\ell\dot{\phi} - \dot{x}_d) + k_d\,(\ell\phi - x_d) \quad \text{..... (3)}$$

where c_d : Damping coefficient of anti-rolling unit

f_c : Reaction force exerted by actuator (f_c=0 in the case of operation in purely passive mode)

f_d : Horizontal component of resultant force exerted on hull by the unit

g : Acceleration of gravity

$\overline{GM}$: Height of metacentre

I : Moment of inertia of hull around its centre of gravity

k_d : Spring constant of anti-rolling unit

ℓ : Distance between centres of gravity of hull and of moving mass

m_d : Mass of moving mass

R : Damping coefficient of hull rolling

T : Exciting moment exerted by wave on hull

W : Displacement of ship

x_d : Horizontal displacement of moving mass in reference to absolute coordinates

ϕ : Rolling angle of hull.

The electric motor driving the moving mass is governed by displacement control: Upon determining experimentally the frequency response to the control input u presented by the horizontal displacement z (= $x_d - \ell\phi$) of the moving mass relative to the hull, the second oder system is approximated by

$$\ddot{z} + 2\zeta_m\,\omega_m\,\dot{z} + \omega_m^2 z = \omega_m^2 u - \ell\ddot{\phi} + g\phi \quad \text{...... (4)}$$

where ω_m : Equivalent angular natural frequency

ζ_m : Equivalent damping ratio

The control system was designed by applying the LQ control theory: Letting $\boldsymbol{x} = [\phi\ z\ \dot{\phi}\ \dot{z}\ ]^T$, and w=T, Eqs. (1)~(4) are expressed in the form of a state equation as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{b}\,u + \boldsymbol{d}\,w \quad \text{.............................. (5)}$$

The evaluation function is given by

$$J = \int_0^\infty \left(\boldsymbol{x}^T\boldsymbol{Q}\,\boldsymbol{x} + ru^2\right)dt \quad \text{.......................... (6)}$$

where $\boldsymbol{Q}$: Weighting matrix

r : Weighting coefficient

For minimizing the control input, the Riccati equation

$$\boldsymbol{PA} + \boldsymbol{A}^T\boldsymbol{P} + \boldsymbol{Q} - \boldsymbol{Pbb}^T\boldsymbol{P}/r = \boldsymbol{0} \quad \text{............. (7)}$$

is solved, which results in

$$u = -\boldsymbol{b}^T\boldsymbol{Px}/r = -\boldsymbol{kx} \quad \text{............................. (8)}$$

3. Anti-rolling unit submitted to test

The ship used for carrying out tests on the hybrid type anti-rolling unit is shown in *Fig. 2*. It is a high-speed shallow-draught survey supervising vessel of approximately 190 t displacement, with the hull forming a chine between the sides and bottom. The anti-rolling unit was installed on an upper structure of an aft deck specially provided for the purpose. The unit is shown in *Figs. 3* and *4*. The moving mass carries within it the driving motor and reduction gearing, and is propelled through a rack-and-pinion mechanism to oscillate on a pair of rails shaped to an inverted arc. Adoption of the arked rails to guide the moving mass oscillation has invested the device with passive functioning character without calling for the cumbersome pendulum and spring suspension mechanism. The hybrid character is invested by the addition of a controlled motor-driven actuator. Weighing a total of 3.5 t, the moving mass represents approximately 1.8% of the vessel displacement. The arked rails guiding the moving mass have been shaped to let the device present a natural period of moving mass oscillation matching that of hull rolling. Free damping of the unit with the oscillating

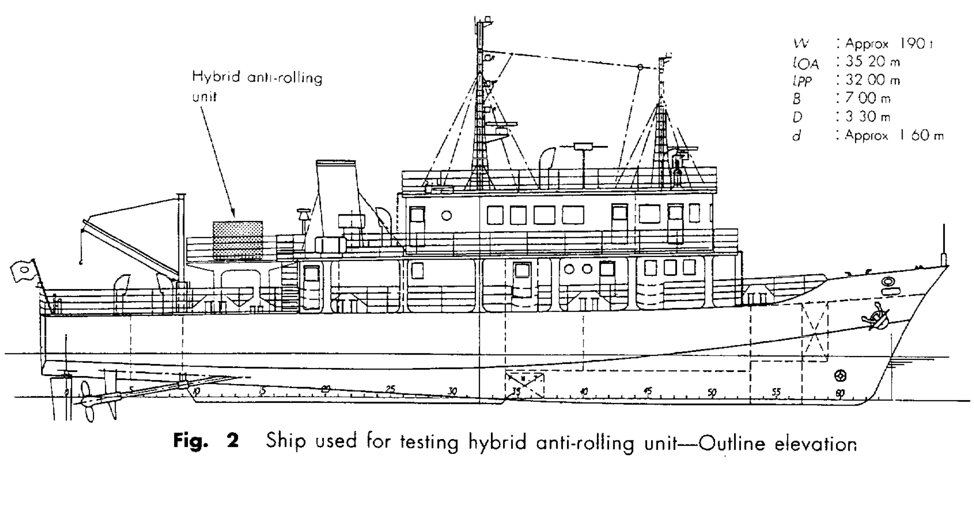


Fig. 2 Ship used for testing hybrid anti-rolling unit—Outline elevation

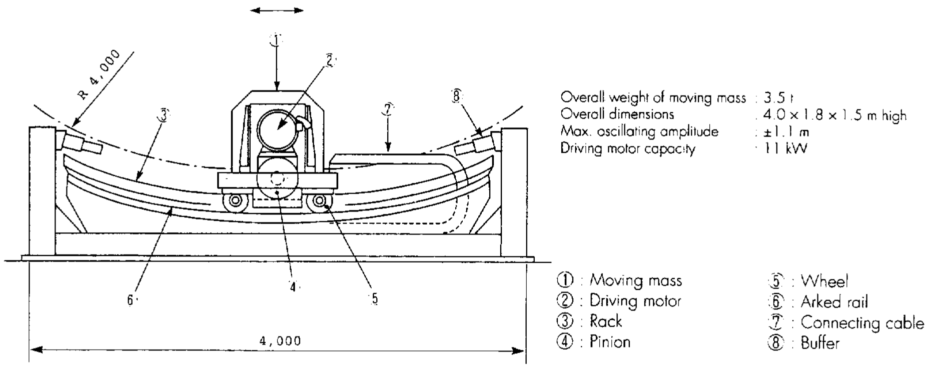


Fig. 3 Hybrid anti-rolling unit—Key components and specification

Fig. 4 Hybrid anti-rolling unit—General view

moving mass dragging the motor while inactivated—i. e. damping of the unit functioning in purely passive mode—proved from the free-oscillation test to provide equivalent viscous damping ratio of approximately 30%.

The control system is configured as shown in *Fig. 5*. The hull is mounted with an angular velocity sensor, and the measured rolling angular velocity is integrated to derive the rolling angle. The velocity and displacement of the moving mass in reference to the hull, on the other hand, are determined from the output of a pulse generator mounted on the driving motor. Control input is derived by summing up the foregoing four data multiplied by the feedback gain determined from Eq. (8).

Prior to operating the unit at sea, its rolling attenuation performance was estimated analytically. The resulting data are shown in *Fig. 6*, where the curves represent the cases of operation in hybrid and passive modes, as well as of non-operation—i. e. with moving mass locked out of operation. The abscissae of the diagrammes in *Fig. 6* are scaled in the ratio between the exciting frequency and the natural frequency of hull rolling. The coordinates represent Φ/Φ_{st} in *Fig. 6*-(a) and $Z/(\ell\Phi_{st})$ in *Fig. 6*-(b), where Φ is the amplitude of hull rolling and Φ_{st} the

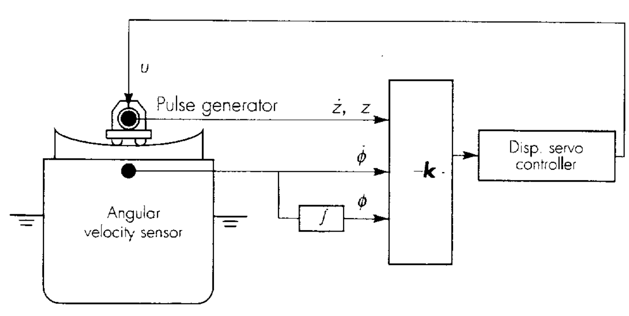
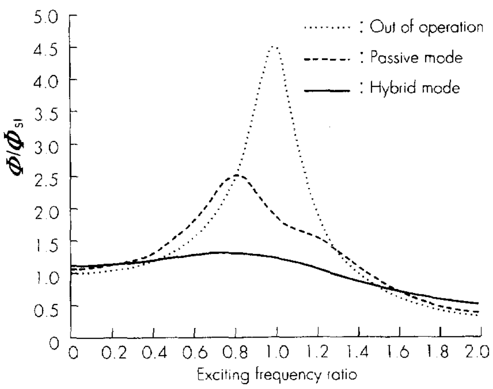
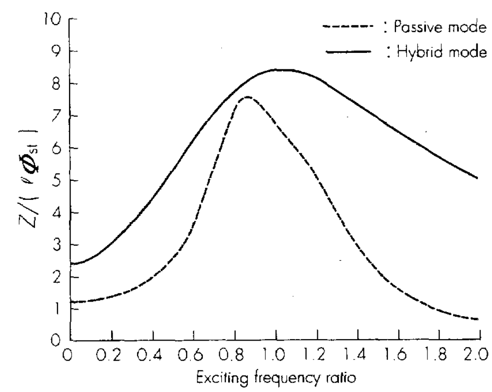


Fig. 5 Control system



(a) Rolling amplitude of hull



(b) Displacement amplitude of moving mass

Fig. 6 Analytically calculated frequency response of anti-rolling unit in different modes of operation

static angle of hull inclination due to the exciting moment exerted by wave, while Z is the displacement amplitude of moving mass upon hull rolling under the same waves. The hybrid mode control system was designed with feedback gain set to attenuate the hull rolling to 1/3 ~ 1/4 compared with non-operation. With the unit operated in passive mode, although not functioning at optimized adjustment of natural period and of damping, it is seen that the rolling amplitude would still be roughly halved compared with the case where the unit is locked out of operation.

4. Shipboard test at sea

4.1 Procedure

The hull rolling attenuation performance effected by the device installed on a ship was measured under wavy conditions during prescribed durations of operation or non-operation of the device. The test was carried out in the following manner.

The location of testing was off Tokyo Bay and around Sagami Bay; the test lasted from February 15 to 18, 1994. Measurements were conducted while the ship was left drifting with waves impinging broadside—a condition of maximum hull rolling—as well as while running with waves impinging broadside and on the quarter—the latter condition to verify performance against long-period rolling excitation. The measurements were repeated with the unit operated in passive mode and with the moving mass locked out of operation. The items and conditions of the test are presented in *Table 1*.

Each measurement lasted 15 minutes; the records taken included time history responses of (a) the hull-rolling angle (b) moving mass displacement and (c) motor torque; the records were thereafter analyzed statistically and spectrographically.

4.2 Results and discussion

The results obtained from the test are given in *Table 2*, which presents data on the hull rolling amplitude and (between parentheses) the percentage of attenuation achieved by actuating the device. The data cover four measurements (a) ~ (d) conducted while the ship was left to drift, and four measurements while running—at slow and at full speed—in waves impinging broadside (measurements (e) and (f)) and on the quarter (measurements (g) and (h)). The natural period of hull rolling proved to be 4.83 s from a test carried out in still water with free hull rolling initiated by actuating the anti-rolling device. The data given in *Table 2* reveal that, with the ship left to drift in broadside waves, both hybrid and passive modes of operation have brought attenuation of hull rolling, with the hybrid mode providing 15 ~ 20% higher attenuation compared with the passive mode, both for maximum amplitude and for 1/3 maximum (significant) amplitude. Of the four measurements, (b) and (d) are seen to have effected the highest rolling attenuation, having brought a reduction to 1/3 in hybrid, and to 1/2 in passive operation mode. Time history responses covering measurement (b) are reproduced in *Fig. 7*, *Table 3* gives the conditions of this measurement. The average hull rolling period was 4.9 s—which roughly coincided with its natural period of 4.83 s given earlier. *Figure 7* reveals that the moving mass functions with an amplitude that is about 10% greater when operated in hybrid than in passive mode. This indicates that the improved performance shown by the unit when operated in hybrid mode is attributable to the enhancement of moving mass oscillating amplitude that can be induced by the controlled drive. The above observation is in good agreement with the results of the calculation presented in *Fig. 6*-(b), which shows an overall higher moving mass

Table 1 Items and conditions of shipboard test at sea

Ship speed	Angle of wave impingement	Mode of operation of anti-rolling device
Drifting	Broadside	Locked out of operation Hybrid mode Passive mode
Approx. 5 kn and Full speed	Broadside	Locked out of operation Hybrid mode Passive mode
	On the quarter	Locked out of operation Hybrid mode Passive mode

Table 2 Results obtained from shipboard test at sea

	Test item	Drifting in broadside waves				Running in broadside w.		Running in w. on quarter	
		(a)	(b)	(c)	(d)	(e) Approx. 5 kn.	(f) Full speed	(g) Approx. 5 kn.	(h) Full speed
Maximum amplitude	Out of operation	6.13	5.81	5.79	4.81	2.77	2.95	5.52	5.02
	Hybrid mode	3.01 (51)	1.91 (67)	3.77 (34)	1.55 (68)	1.59 (43)	2.39 (19)	3.01 (45)	2.72 (46)
	Passive mode	4.00 (35)	2.86 (51)	4.40 (23)	2.83 (41)	2.01 (28)	3.22 (−9)	5.76 (−4)	—
1/10 maximum amplitude	Out of operation	4.70	4.38	4.29	4.07	2.03	2.19	4.35	3.49
	Hybrid mode	2.18 (54)	1.46 (67)	2.88 (33)	1.35 (67)	1.04 (49)	1.97 (10)	2.46 (43)	2.42 —
	Passive mode	2.90 (38)	2.23 (49)	3.42 (20)	2.51 (38)	1.73 (15)	2.51 (−15)	4.39 (−1)	—
1/3 maximum amplitude	Out of operation	3.77	3.25	3.41	3.44	1.60	1.76	3.55	2.82
	Hybrid mode	1.70 (55)	1.16 (64)	2.16 (37)	1.17 (66)	0.82 (49)	1.59 (10)	1.97 (45)	2.03 (28)
	Passive mode	2.33 (38)	1.66 (49)	2.70 (21)	1.98 (42)	1.56 (15)	1.99 (−13)	3.41 (4)	—
Mean amplitude	Out of operation	2.43	2.05	2.11	2.35	1.04	1.16	2.26	1.84
	Hybrid mode	1.13 (53)	0.74 (64)	1.35 (36)	0.79 (66)	0.53 (49)	0.47 (16)	1.28 (43)	1.38 (25)
	Passive mode	1.53 (37)	1.07 (48)	1.76 (17)	1.32 (44)	0.87 (16)	1.26 (−9)	2.15 (5)	—

Note: Given between parentheses are the percentage attenuation brought by device actuation

$$\left(1 - \frac{\text{Hull rolling amplitude with device out of operation}}{\text{Ditto with device in operation}}\right) \times 100\%$$

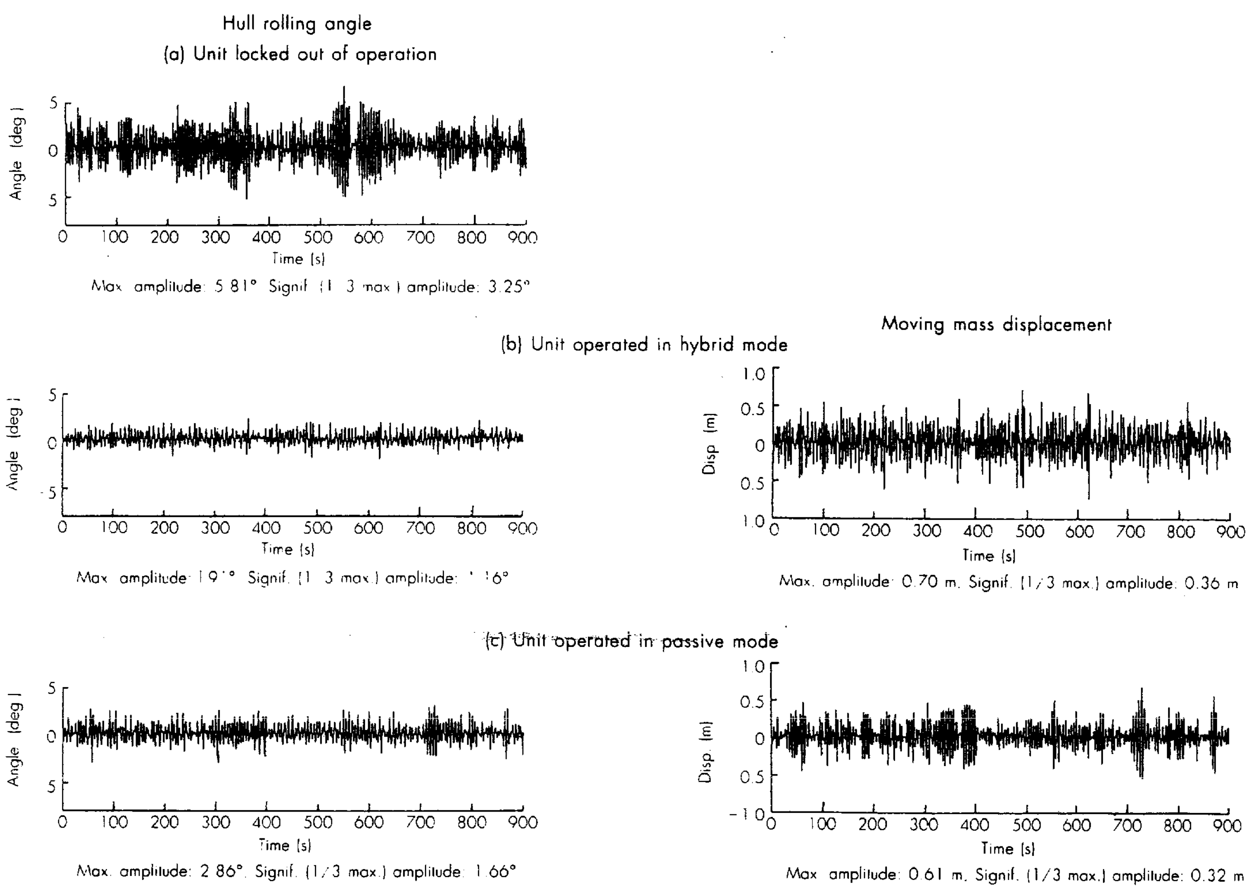


Fig. 7 Time history responses recording anti-rolling unit performance —Measurement (b): Waves impinging broadside

Table 3 Test conditions of measurement (b)

Area where test was conducted	Tokyo Bay entrance, off Jogashima Island
Date of test	Feb. 16, 1994
Weather	Clear
Wave height measured by eye	0.25 m
Wave length measured by eye	5~6 m
Angle of wave impingement measured by eye	90° on starboard side
Wind speed	6 m/s
Wind direction	40°~90° on starboard side
Ship speed	0 knot

oscillating amplitude in hybrid (solid line) than in passive (broken line) mode. The relatively poor performance obtained in measurement (c) as compared with other measurements can be attributed to the average hull rolling period being approximately 5.1 s in this measurement—which is somewhat longer than its natural period of 4.83 s.

With regards to measurements made with waves impinging on the quarter, it is known that with conventional passive type devices, such as the anti-rolling tank system, hull rolling is aggravated instead of being attenuated by setting the device to work under such a condition of wave impingement. The same applies to the present results for measurement (g) in *Table 2* for hull amplitude. Operated in hybrid mode, however, attenuation of hull rolling by approximately 1/2 is seen to have been obtained for the corresponding condition. The time history responses recorded in measurement (g) are reproduced in *Fig. 8*, *Table 4* summarizes the conditions applicable to this measurement. The average hull rolling period was 5.3 s—appreciably longer than the natural period. It is seen, however, that the hybrid mode of operation—with the device exerting considerable supplementary damping—has widely extended the frequency range of high rolling attenuation. This promises amply satisfactory performance even against long-period rolling likely to be encountered during actual service at sea.

5. Conclusion

A device for attenuating hull rolling when the ship is drifting and when running at slow speed has been developed, and a unit incorporating a moving mass of 3.5 t has been designed for installation on a survey supervising vessel of approximately 190 t displacement. The results of the test at sea carried out on the vessel thus

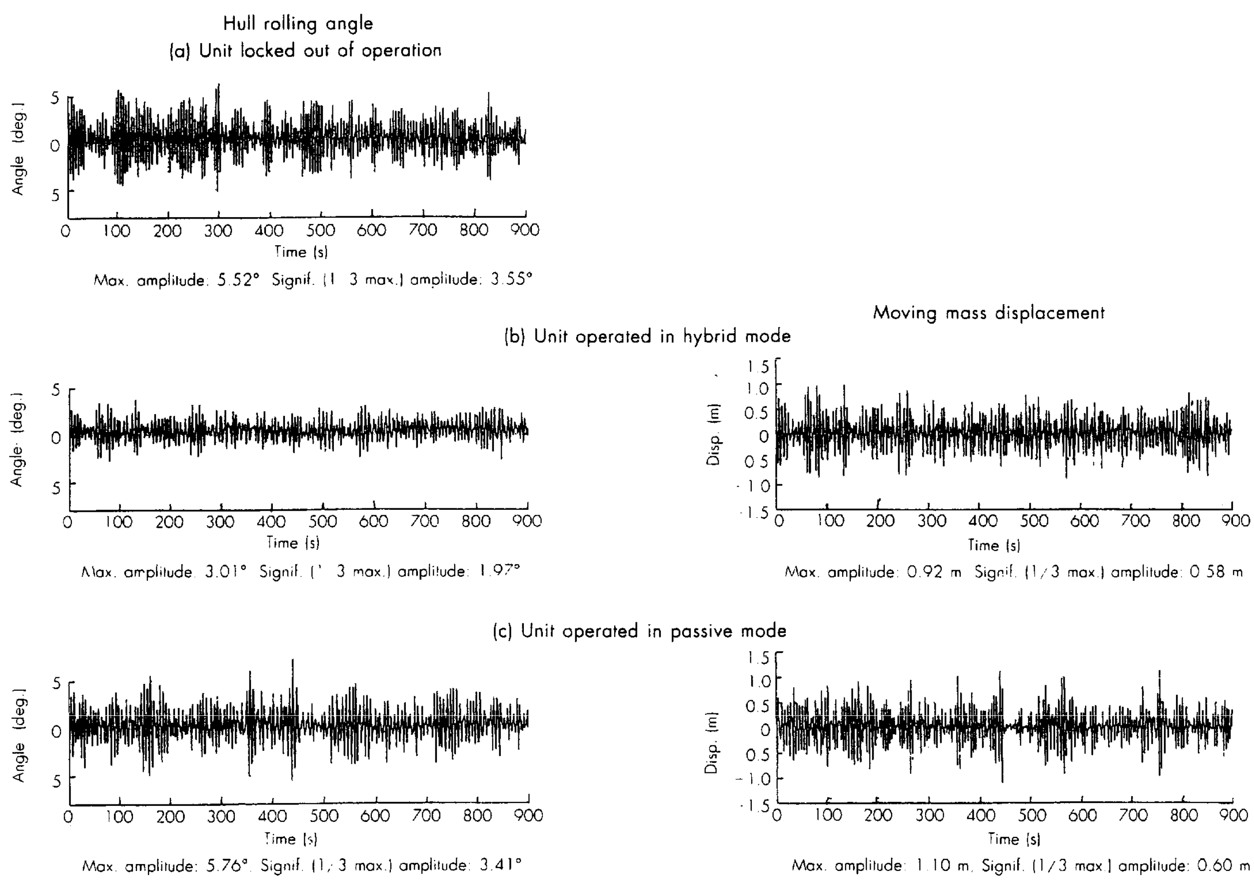


Fig. 8 Time history responses recording anti-rolling unit performance —Measurement (g): Waves impinging on the quarter

Table 4 Test conditions of measurement (g)

Area where test was conducted	Tokyo Bay entrance, off Jogashima Island
Date of test	Feb. 17, 1994
Weather	Clear
Wave height measured by eye	0.6 m
Wave length measured by eye	8 m
Angle of wave impingement measured by eye	135° on starboard side
Wind speed	5~7 m/s
Wind direction	110°~150° on starboard side
Ship speed	5.3 knots

equipped proved that:

(1) Adoption of the hybrid mode of operation permits attenuating rolling to approximately 1/3 on a ship left to drift. This corresponds to an improvement of roughly 15% over what is possible with a purely passive-type of device—such as that represented by the anti-rolling tank system.

(2) Even when the ship is running with waves impinging on the quarter—a condition in which it is difficult for passive devices to function effectively—the hybrid type device can attenuate hull rolling to approximately 1/2 with the moving mass oscillating in controlled phase.

(3) The results obtained from the test agreed well with what was predicted from theoretical calculations.

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